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THE JOHNS HOPKINS UNIVERSITY

Applied Physics Laboratory
Silver Spring, Md.

Operating under a "Section T" Contract
with the Bureau of Ordnance
U. S. Navy

SUGGESTED SERVO CONTROL SYSTEM FOR BUMBLEBEE WITH PRELIMINARY THEORETICAL ANALYSIS.

TC Report CM-12

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February 13, 1945

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Suggested Servo Control System for Bumblebee with Preliminary Theoretical Analysis.

1. SUMMARY:

A general plan is described for a servo system which automatically stabilizes the bumblebee about the roll, yaw, and pitch axes and steers it in elevation and traverse. A schematic diagram of a representative system is shown in Figure 1.

Equations are written governing the stabilization and steering response based upon assumptions regarding the action of the various components. General assumptions are:

A. The response of the whole system, and each part in particular, is linear.

B. Backlash, dead space, noise in the radar signal, leakage, and dry friction are negligible.

C. The response of the bee about any one of the three axes is independent of its response about the other two.

Some of the general conclusions arrived at are:

a. It appears that a stabilization-steering system using two free gyros may be possible. This will depend upon the ability of the roll system to stop the spin. Otherwise a rate gyro connected in series with the roll free gyro may be necessary.

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b. Stability of the stabilization-steering system can be adjusted by feeding back to the error signal an anti-hunt signal proportional to the displacement of the control surfaces.

c. The steady state stabilization about the three independent axes with no steering signal is theoretically perfect.

d. For a missile which is aerodynamically stable about the pitch and yaw axes, the response to a constant steering signal is a constant percentage of that signal.

e. For a missile which has neutral stability about the yaw (or pitch) axis, the response to a constant steering signal is perfect.

f. The over-all stability of the control system depends heavily upon:

i) The static stability coefficient of the missile,

ii) The damping constant of the missile,

iii) The feedback coefficient,

and to some extent upon all the other parameters of the system.

g. The constant velocity lag during steering of the simplest system can be eliminated theoretically by the addition of integral error control on the ground or in the bee.

h. Formulas for the amplitude ratio of the bumblebee response to sinusoidal target motions (or radar errors) are given, but numerical calculations have not been made because of the lack of information on the expected range of the parameters.

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1. The feedback in the stabilization system can be adjusted to make the stabilization system stable even when the static stability coefficient K_2 of the missile is negative. It is not evident that the corresponding statement holds for the overall steering-stabilization system.

I: STABILIZATION SYSTEM

2. <u>General Plan for Stabilization</u>. -- A general plan for stabilizing the bee about the three axes is proposed. The system is similar to the Sperry Automatic Pilot. As visualized at present it will operate for roll axis stabilization somewhat as follows:

<u>Roll Axis Stabilization</u>. -- A free gyro is mounted with the axis of the outer gimbal parallel to the center line of the bee. Upon launching, the gyro is uncaged so that the spin axis is vertical. Any rotation about the axis of symmetry will induce an error signal, such as a pressure difference, in the pneumatic pickoffs. The difference in pressure operates a diaphragm attached to a balanced oil valve restrained by a spring which makes it seek a neutral position. As the valve is opened and closed, oil, under pressure, flows into a piston whose displacement moves the control surfaces on the bee. At the same time it feeds back a signal on the pickoffs to decrease the error signal. This feedback is used to make the system stable. The action of the aerodynamic forces on the control surfaces causes the bee to rotate about its roll axis in a direction opposite to that of the error signal.

Since this is a pneumatic-hydraulic mechanical system, the need for sources of electrical power is eliminated. Of course, if a generator is installed to furnish an electrical supply for the electronic equipment, it might be possible to replace the pneumatic pickoff with an electrical one. The power for the hydraulic servo has been thought of as pressure generated in a tank by chemical action such as that of slow burning

cordite. It may be found that an air turbine can be used for power without additional cost in rag; however, the problem of gearing down the high speed would probably be insurmountable. If the hydraulic servo is used, it seems desirable to build a system which will not waste the oil from the servo but will recirculate it. The decision as to whether or not it is cheaper to build the additional oil pump rather than to waste oil depends upon the amount of oil required if not circulated. One aim in the design should be to make it possible to set the controls in a fixed position without losing oil.

Yaw and Pitch Stabilization Systems. -- The combination stabilization system for yaw and pitch will be like that for roll with the following additions. A different free gyro will be used, which must be equipped with pickoffs indicating errors about both the yaw and pitch axes. Furthermore, a gyro precessing mechanism, assumed now to be an air source, will be needed for steering. Radar error signals will control the precession either (a) automatically from the missile, or (b) from the ground. The combination of pickoffs, precessing mechanism, and feedback mechanisms on the pitch-yaw gyro seems to be the most complicated part of the control servo mechanism.

3. Schematic Diagram of the Control Servos. -- The diagram of Fig. 1 is a schematic representation of the system for servo control about the yaw or pitch axis. Box (I) may be spoken of as the stabilization part and box (II) the steering part of the system. The roll stabilization system may be represented by another box like (I).

4. Equations of Components of the Stabilization System. --

Equations representing the performance of each part of the system in (I) of Figure 1 will now be written under the following assumptions:

A. The whole system, as well as each of the parts, is linear.

SCHEMATIC DIAGRAM OF CONTROL SYSTEM CM-12

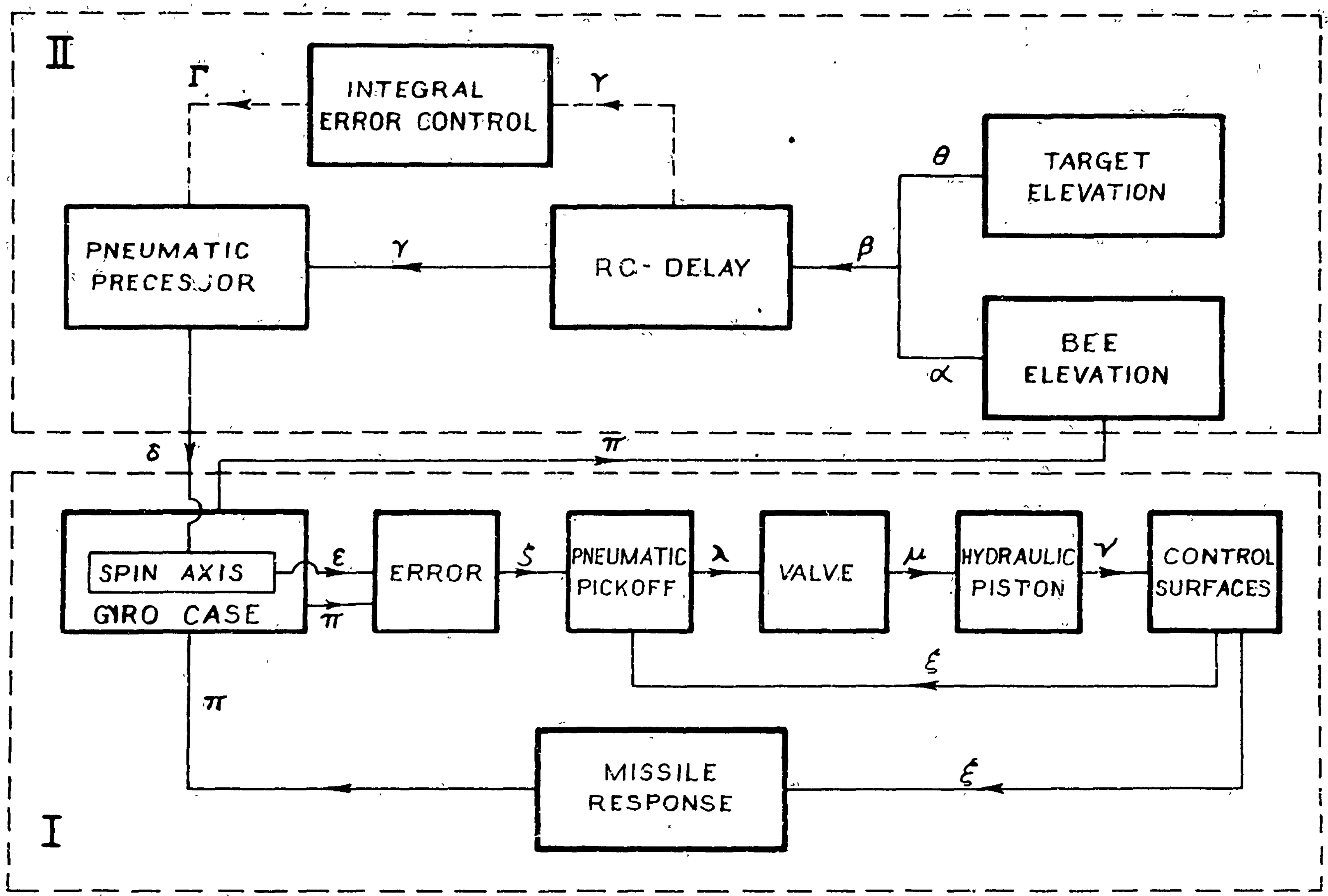

Fig. 1

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B. Backlash, dead space, leakage, radar noise, and dry friction are negligible.

C. Control about the three axes is mutually independent.

Equations of Performance of Components.

(1)	$\zeta = \pi - \varepsilon$	ERROR SIGNAL
(2)	$\lambda = C_3(\zeta - C_4 \xi)$	PICKOFF
(3)	$(J_1p^2 + F_1p + K_1)\mu = C_5K_1 \lambda$	VALVE
(4)	$p \nu = C_6 \mu$	HYDRAULIC PISTON
(5)	$\xi = C_7 \nu$	CONTROL SURFACES
(6)	$(J_2p^2 + F_2p + K_2)\pi = -C_8 \xi$	MISSILE RESPONSE

where

ε = angular displacement of gyro spin axis measured from a fixed zero position.

π = angular displacement of bee (and gyro case) from same zero as used for ε.

$\zeta = \pi - \varepsilon$ = angular error between the case axis and the spin axis.

λ = displacement of pickoff from neutral position.

ξ = displacement of control surface from neutral position.

C_3 = displacement of pneumatic pickoff per unit error signal without feedback.

C_4 = proportionality feed back constant.

J_1 = mass of valve.

F_1 = coefficient of viscous friction of valve.

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K_1 = spring constant of restraining spring on the valve.

μ = linear displacement of valve.

C_5 = displacement of valve per unit displacement of pickoff.

$p = \frac{d}{dt}$ = differential operator.

ν = displacement of hydraulic piston measured from the neutral position.

C_6 = velocity of piston per unit displacement of valve.

C_7 = displacement of control surface per unit displacement of the piston.

J_2 = moment of inertia of missile about its axis of response.

F_2 = the damping constant of the missile.

K_2 = missile static stability constant.

C_8 = rotational torque on the missile per radian displacement of the control surface.

Equation (6) with $K_2 > 0$ implies aerodynamic stability of the missile about the appropriate axis. In other words, the missile is effectively spring-restrained about the axis, the angular position of the missile in which the spring exerts no force being the stable position. The angles π and ε are both measured from the fixed stable position. During free flight (no steering signal) the spin axis of the free gyro will be so aligned that $\varepsilon = 0$. The flight of the missile will be controlled by precessing the axis of the free gyro away from the fixed zero position.

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5. <u>Equations for the Stabilization System.</u> -- A single equation relating the angular displacement of the bee to that of the gyro axis may be obtained by eliminating ζ, λ, μ, ν, and ξ from equations (1)-(6).

The resulting differential equation is

$$(7)\quad \left[(J_1p^3 + F_1p^2 + K_1p + K_1A)(J_2p^2 + F_2p + K_2) + BK_1\right]\pi = BK_1$$

where

$$(8)\quad A = C_7C_6C_5C_4C_3 \quad , \qquad B = C_8C_7C_6C_5C_3 = \frac{C_8}{C_4}A.$$

It will now be assumed that the mass of the valve J_1 and the coefficient of viscous friction F_1 on the valve are negligible. If this assumption should turn out to be incorrect, the following results will be only approximate. Thus, setting $J_1 = F_1 = 0$ in (7) and dividing both sides by K_1, the equation between π and ε reduces to

$$(9)\quad \left[J_2p^3 + (F_2 + AJ_2)p^2 + (K_2 + AF_2)p + (AK_2 + B)\right]\pi = B\varepsilon$$

In order that the solution of (9) be stable it is necessary and sufficient that

A. All coefficients on the right side of (9) be positive, and

B. $(F_2 + AJ_2)(K_2 + AF_2) > J_2(AK_2 + B)$.

This stability inequality can be simplified to

$$(10)\qquad A^2F_2J_2 + AF_2^{\,2} + F_2K_2 > BJ_2 \ .$$

The feedback coefficient C_4 is a factor of A; therefore, theoretically the feedback can be increased sufficiently to satisfy (10) and make the system stable. Major factors determining the value of A to give stability are J_2, F_2, and K_2, all of which represent aerodynamical properties of the bee, and none of which are known. Actually J_2, F_2, and K_2 will be

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chosen and then A will be adjusted to make the system stable when the controls are acting.

If J_2, K_2, F_2 and the constant $B = C_8C_7C_6C_5C_3$ are such that $F_2K_2 > J_2B$, the system will be stable without feedback.

6. <u>Stabilization when the Gyro Spin Axis is Aligned so that $\varepsilon = 0$.</u> -- Assuming that the bee is stable about the axis under consideration (roll, pitch, or yaw), and that the axis of the corresponding free gyro is aligned with the stable position of the missile, the response of the bee to an angular displacement π from the stable position is described by equation (9) with $\varepsilon = 0$. The solution of the equation is then

$$(11) \quad \pi = D_1e^{x_1t} + D_2e^{x_2t} + D_3e^{x_3t}$$

where D_1, D_2, D_3 are constants depending on the initial conditions and x_1, x_2, x_3 are the three roots of the cubic equation

$$(12) \quad J_2x^3 + (F_2 + AJ_2)x^2 + (K_2 + AF_2)x + (AK_2 + B) = 0.$$

If the coefficients of (12) are all positive and inequality (10) is satisfied, the real parts of the roots x_1, x_2, x_3 will be negative; hence, the solution (11) will contain only transient terms and the bee will return to its stable position $\pi = 0$:

7. <u>Stabilization in Yaw or Pitch when $\varepsilon = \varepsilon_0$ (a constant).</u> -- Again assuming that the bee is stable about the axis under consideration, but now assuming that the axis of the corresponding free gyro is at an angle ε_0 with the stable position of the missile, the response of the bee to an angular displacement π from the stable position is described by equation (9) with $\varepsilon = \varepsilon_0$. The steady state solution of this equation is

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(13) $$\pi = \frac{B}{AK_2 + B}\,\varepsilon_0$$

and the transient solution is given by (11). The stability criteria are unchanged.

It follows from equation (13) that the bee returns to a position which is between the stable position and the position of the gyro axis. The missile attempts to return to the position of the gyro axis, but is prevented because it is effectively spring-restrained about the stable position.

If the bee is neutrally stable#, that is $K_2 = 0$, equation (13) reduces to $\pi = \varepsilon_0$. In this case the missile actually does return to the position of the gyro axis.

8. <u>Rate Gyro for Additional Roll Stabilization</u>. -- If the roll stabilization system violates the assumption of linearity violently due to the high angular velocity at launching so that the analyses do not apply, it is possible that the free gyro control alone will not stop the spinning. In such a case it might still be possible to add a rate gyro with its input axis along the roll axis, as has been suggested by various people. The output of this gyro could be fed into the error signal channel with the possible elimination of the feedback link on the free gyro. In this combination system, the free gyro would be used to furnish the error signal and the rate gyro to furnish the derivative of the error signal.

\# Throughout this report it is assumed that the bee is either stable or neutrally stable about each of the three axes. As stated elsewhere, it might develop that a higher degree of maneuverability can be obtained if the missile is made slightly unstable, that is, if K_2 is negative. All of the equations of this report hold equally well for K_2 negative, but the conclusions regarding stability must be revised. The over-all stability of the system is a strong function of J_2, F_2, K_2 and A whose values are still unknown.

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II. STEERING SYSTEM

9. <u>Equations of Components of Elevation Steering Mechanism.</u> -- Figure 1 indicates that the steering control will operate as follows:

The radar equipment on the ground will form a signal which is the difference between the elevation of the target and the elevation of the missile. This error signal will be delayed by an RC circuit in the T and E scope to give smoothing. The smoothed error signal then will act in the bee through a pneumatic precessor to change the direction of the spin axis of the pitch-yaw gyro.

The equations of performance of the various parts of the steering mechanism in Figure 1 may be written as follows:

(14)	$\beta = \theta - \alpha$	ERROR SIGNAL
(15)	$(\tau p + 1)\gamma = \beta$	RC DELAY
(16)	$\delta = C_1\gamma$	PNEUMATIC CONTROL VALVE DISPLACEMENT
(17)	$p\epsilon = C_2\delta$	SPIN AXIS DISPLACEMENT
(18)	$p\alpha = C_9 p\pi$	PATH RESPONSE

where

θ = the elevation of the target in fixed space.

α = the elevation of the missile in fixed space.

$\beta = \theta - \alpha$ = the difference in elevation of the target and missile.

τ = the time constant of the RC delay circuit.

γ = the smooth output error signal.

δ = the precessing force on the spin axis of the gyro.

C_1 = the force on the gyro spin axis per unit smoothed error signal.

C_2 = velocity of spin axis precession per unit applied force.

C_9 = rate of change of the elevation of the missile per unit angular velocity of the missile about its pitch axis.

The first four of the set of equations (14)-(18) represent the manner in which the error signal from the ground radar is used to process the gyro spin axis, thereby setting a new course. When this spin axis has been precessed through the angle ε, an error signal appears in the stabilization system, causing the missile to respond as described in the previous paragraphs on stabilization. The change in orientation of the missile causes a change in its path and in its elevation, thus reducing the error signal at the radar. This change in path elevation due to change in missile orientation is described by equation (18).

Assumptions A), B), and C) of section 4 have been carried over and apply to the steering system. The actual relation between α and π is not that given by equation (18) but rather

$$(19) \quad p\pi = p\alpha + \frac{R}{\dot{R}} p^2\alpha$$

where

R = range of the missile,

and $\dot{R}$ = range rate of the missile.

Equation (19) is linear, but the coefficient $\frac{R}{\dot{R}}$ varies with time. In order to simplify the mathematical analysis, the approximate relation (18) is used in place of (19). Tests may show that range influences stability of the missile, but the present analysis will not uncover this effect because (19) has been replaced by (18). If stability does happen to decrease with range, it might be possible to vary the wheel speeds of the gyros to adjust for the difference.

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10. **Steering Control about Pitch Axis - No Integral Control.**-- When the variables β, γ, δ, ε, ζ, λ, μ, ν, π, and ξ are eliminated from equations (1)-(6) and (14)-(18) inclusive, and F_1 and J_1 have been replaced by 0, the equation of the response of the missile becomes

$$(20)\quad \left[\tau J_2 p^5 + (\tau F_2 + \tau A J_2 + J_2)p^4 + (\tau K_2 + \tau A F_2 + F_2 + A J_2)p^3 + (\tau A K_2 + \tau B + K_2 + A F_2)p^2 + (A K_2 + B)p + C_9 C_2 C_1 B\right]\alpha = C_9 C_2 C_1 B \theta .$$

A study of equation (20) leads to the following conclusions:

1. For a constant target angle $\theta = \theta_0$ the steady state elevation of the missile is also $\alpha = \theta_0$.

2. For a target whose angular velocity in elevation is a constant, that is, $\theta = nt$, the elevation of the missile is given by

$$(21)\qquad \alpha = nt - \frac{(C_4 K_2 + C_8)n}{C_9 C_8 C_2 C_1},$$

   so that it is seen that there is a constant velocity lag of

$$\frac{(C_4 K_2 + C_8)n}{C_9 C_8 C_2 C_1} .$$

3. The stability of the system depends only on the left member of equation (20), the actual stability criteria being

   A. All of the coefficients are positive, and

   B. A certain pair of inequalities exists between the coefficients of this left member.

   As a first approximation, we neglect the fifth order term in (20) and write the stability criterion as

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$$(22)\quad (AK_2 + B)\Big[(\tau AF_2 + \tau B + K_2 + AF_2)(\tau F_2 + \tau AF_2 + F_2 + AJ_2) - C_9C_2C_1B(\tau F_2 + \tau AJ_2 + J_2)\Big] > C_9C_2C_1B(\tau F_2 + \tau AF_2 + F_2 + AJ_2)^2$$

4. It is theoretically possible to vary A to make the system aerodynamically stable.

11. <u>Steering Control about Yaw Axis - No Integral Control</u>. -- If the missile is designed to be stable about the yaw axis, the system described in Sections 9 and 10 for pitch apply verbatim. However, to get greatest maneuverability of the missile, it may be necessary to make it have neutral stability about the yaw axis. In such a case the static coefficient of stability K_2 about the yaw axis becomes 0. Substituting $K_2 = 0$ in equations (20), (21), and (22) leads to corresponding results for the response of a missile which is neutrally stable about the yaw axis given by

$$(23)\quad \Big[\tau J_2p^5 + (\tau F_2 + \tau AJ_2 + J_2)p^4 + (\tau AF_2 + F_2 + AJ_2)p^3 + (\tau B + AF_2)p^2 + Bp + C_9C_2C_1B\Big]\alpha = C_9C_2C_1B\theta ,$$

$$(24)\quad \alpha = nt - \frac{n}{C_9C_2C_1} ,$$

$$(25)\quad \Big[(\tau B + AF_2)(\tau AF_2 + F_2 + AJ_2) - C_9C_2C_1B(\tau F_2 + \tau AJ_2 + J_2)\Big] \quad C_9C_2C_1(\tau AF_2 + F_2 + AJ_2)^2 .$$

Conclusions corresponding to those for pitch may be drawn.

12. <u>Integral Control - Pitch</u>. -- The equations for the response of the missile to a steering signal given in equation (21) show that there will be a steady state constant velocity lag for a target whose angular velocity in elevation is constant. As this is the approximate condition which will

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hold during the anticipated operation of the missile, an attempt has been made to eliminate this constant velocity lag. Two alternatives are possible depending upon whether the missile is automatically controlled

A. From the ground, or

B. In the air.

If the control is from the ground, a computer may be developed which will generate the constant velocity lag given in (21). It may be noticed that the computer will solve an equation which involves known constants and the angular velocity of the target in elevation. Such a computer could be made from a rate gyro whose sensitivity is set at the constant value of

$$\frac{AK_2 + B}{C_9C_2C_1B} = \frac{C_4K_2 + C_8}{C_9C_8C_2C_1}\ .$$

A second gyro for traverse computation would also be needed.

If the control is going to be generated on the ground or in the missile, the error signal which has been used in the previous discussions will be replaced by error plus integral error control.# This would necessitate additional equipment which would give an extra feeding channel between the error indicator and pneumatic precessor in Figure 1. This channel would produce the integral of the error so that its equation of performance may be written as

$$(26) \qquad p\Gamma = \gamma$$

where Γ = integral error control feedback signal. The performance of the pneumatic precessor is now changed from (16) to

If the integral error control is generated in an electric circuit, it may not be possible to give pure integral control but very easy to get control, approximating the desired type, represented by the equation

$$p\Gamma = (1 + \tau_1 p)\gamma$$

(27) $\delta = C_0 \Gamma + C_1 \gamma$.

When the variables are eliminated in the equations (1)-(6) (with $F_1 = J_1 = 0$) and equations (14), (15), (26), (27), (17) and (18), the equation for the response of the missile about the pitch axis with integral control becomes

(28) $$\left[\tau p^6 + (\tau F_2 + \tau A J_2 + J_2)p^5 + (\tau K_2 + \tau A F_2 + F_2 + AJ_2)p^4 + (\tau A K_2 + \tau B + K_2 + AF_2)p^3 + (AF_2 + B)p^2 + C_9C_2C_1Bp + C_9C_2C_0B\right]\alpha = \left[C_9C_2C_1Bp + C_9C_2C_0B\right]\theta .$$

A study of this equation indicates that

A. When the target elevation remains constant, the steady state elevation of the missile is also equal to that constant.

B. The constant velocity lag for a target whose elevation angular velocity is constant ($\theta = nt$) is zero.

C. The transient response of the system is changed from that described in the system of equation (20), but the parameter A which includes the feedback is still available for adjusting the stability of the system.

13. Integral Control - Yaw. -- Again the equations of the preceding Section describing response of the missile about the pitch axis when the integral error control has been added to the servo system applies equally well for the response about the yaw axis, provided the missile is stable about this axis. If, on the other hand, it has neutral stability about the yaw axis, we can replace $F_2 = 0$ in equation (28) and obtain an equation for the response in this case given by

(29) $$\left[\tau p^6 + (\tau F_2 + \tau A J_2 + J_2)p^5 + (\tau A F_2 + F_2 + AJ_2)p^4 + (\tau B + AF_2)p^3 + Bp^2 + C_9C_2C_1Bp + C_9C_2C_0B\right]\alpha = \left[C_9C_2C_1Bp + C_9C_2C_0B\right]\theta .$$

Conclusions similar to (A) and (B) still hold. The transient response is governed by an equation different from that of Section 10 or 12.

14. <u>Amplification of Sinusoidal Motion</u>. -- If the target flies a course such that $\theta = A \sin \omega t$ or if the radar tracking error has this form, then the steering signal input is a sine function. The position angle α, based on the equations and assumptions above, would be given by $\alpha = \rho A \sin (\omega t + \sigma)$ where ρ is the amplification factor; that is the ratio of the amplitude of the output (ρA) to the amplitude of the input (A), and σ is the phase lag between the input and response. The values of ρ and σ are tabulated for each of the cases considered previously.

A. Steering about the Pitch Axis - No Integral Control.

$$\rho = \frac{C_9C_2C_1B}{\sqrt{\left[(\tau F_2+\tau AJ_2+J_2)\omega^4 - (\tau AK_2+\tau B+K_2+AF_2)\omega^2 + C_9C_2C_1B\right]^2 + \left[\tau J_2\omega^5 - (\tau K_2+\tau AF_2+F_2+AJ_2)\omega^3 + (AK_2+B)\omega\right]^2}}$$

(30)

$$\sigma = -\,\mathrm{Tan}^{-1}\left[\frac{\tau J_2\omega^5 - (\tau K_2+\tau AF_2+AJ_2)\omega^3 + (AK_2+B)\omega}{(\tau F_2+\tau AJ_2+J_2)\omega^4 - (\tau AK_2+\tau B+K_2+AF_2)\omega^2 + C_9C_2C_1B}\right]$$

B. Steering about the Pitch Axis - Integral Control.

$$\rho = \frac{\sqrt{(C_9C_2C_1B\omega)^2 + (C_9C_2C_0B)^2}}{\sqrt{\left[-\tau\omega^6 + (\tau AF_2+F_2+AJ_2)\omega^4 - B\omega^2 + C_9C_2C_0B\right]^2 + \left[(\tau F_2+\tau AJ_2+J_2)\omega^5 - (\tau B+AF_2)\omega^3 + C_9C_2C_1B\omega\right]^2}}$$

(31)

$$\sigma = \mathrm{Tan}^{-1}\frac{C_1\omega}{C_0} - \mathrm{Tan}^{-1}\left[\frac{(\tau F_2+\tau AJ_2+J_2)\omega^5 - (\tau B+AF_2)\omega^3 + C_9C_2C_1B\omega}{-\tau\omega^6 + (\tau AF_2+F_2+AJ_2)\omega^4 - B\omega^2 + C_9C_2C_0B}\right]$$

C. Steering about the Yaw Axis - Stable - No Integral Control.

ρ - Same as A.

σ - Same as A.

D. Steering about the Yaw Axis - Stable - Integral Control.

ρ - Same as B.

σ - Same as B.

E. Steering about Yaw Axis - Neutral Stability - No Integral Control.

Set $K_2 = 0$ in (30)

F. Steering about Yaw Axis - Neutral Stability - Integral Control.

Set $K_2 = 0$ in (31)

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ABSTRACT

A general plan is described for a servosystem which automatically stabilizes the Bumblebee about the roll, yaw, and pitch axes and steers it in elevation and traverse. The over-all stability of the control system depends upon the static stability coefficient of the missile, the damping constant of the missile, the feedback coefficient, and, to some extent, upon all the other parameters of the system. Formulae for the amplitude ratio of the Bumblebee response to sinusoidal target motions (or radar errors) are given, but numerical calculations have [illegible] been made because of the lack of information on the expected range of the paramet[illegible] 17

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